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Temperature and rainfall extremes change under current and future global warming levels across Indian climate zones

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ABSTRACT

Mean surface temperature is projected to rise by about 4.4 °C by the end of the century compared to the period between 1976 and 2005 when following the most extreme scenario of the greenhouse gas emissions pathway (Krishnan et al., 2020). With this rise in mean temperature, there is a lot of uncertainty on how weather and climate extremes would unfold, especially for various climate zones of India. It is therefore essential that the potential changes in both magnitude and direction of weather and climate extremes at the regional level when the global temperature reaches the different warming levels from 1 °C to 3 °C be established to allow for informed policy formulation.

The present study explores the potential changes in the Expert Team on Climate Change Detection and Indices of rainfall and temperature estimated from the coupled model inter-comparison project CMIP5 multi-model ensemble over different climatic zones of India at 1 °C, 1.5 °C, 2 °C, 2.5 °C and 3 °C global temperature rise relative to pre-industrial levels under two Representative Concentration Pathways, RCP4.5 and RCP8.5. Projected changes in temperature extremes indicate significant changes at all warming levels across the nine climate zones of India. Hot temperature extremes are expected to increase while cold temperature extremes decrease. For India, country average at 3 °C under the RCP8.5 and 2 °C under the RCP4.5 scenarios, ensemble median shows that Warm Spell Duration Index will increase by 131 days and 66 days; hot days increase by 44% and 52%, warm nights increase by 23% and 13%; cold days decrease by 10% and 9%, and cold nights decrease by 13% and 12% relative to pre-industrial levels. The greatest changes in temperature based indices are projected in the colder northern parts of the country followed by the arid zone. Ensemble median for rainfall indices shows an increase in high precipitation indices, though with large model spread indicating the large uncertainties in the projections. Annual total precipitation and heavy rainfall related extreme indices show statistically significant increases in the tropical, temperate and semi-arid regions of India, moving from 1 °C to 3 °C warming level under RCP8.5 scenario whereas there is generally no significant change in the maximum number of consecutive dry and wet days.

Moreover, the potential changes in climate extremes at the regional level are expected to have far-reaching impacts on the social and economic statuses of the respective climate zones. This information at a regional scale also calls attention to the national and state action plan on climate change and adaptation to be more responsive in order to take coherent and integrated policy decisions.

1. Introduction

The Paris Agreement committed signatories to ‘limiting the global average temperature to well below 2 °C above pre-industrial levels and to further pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, in order to reduce the future risks and

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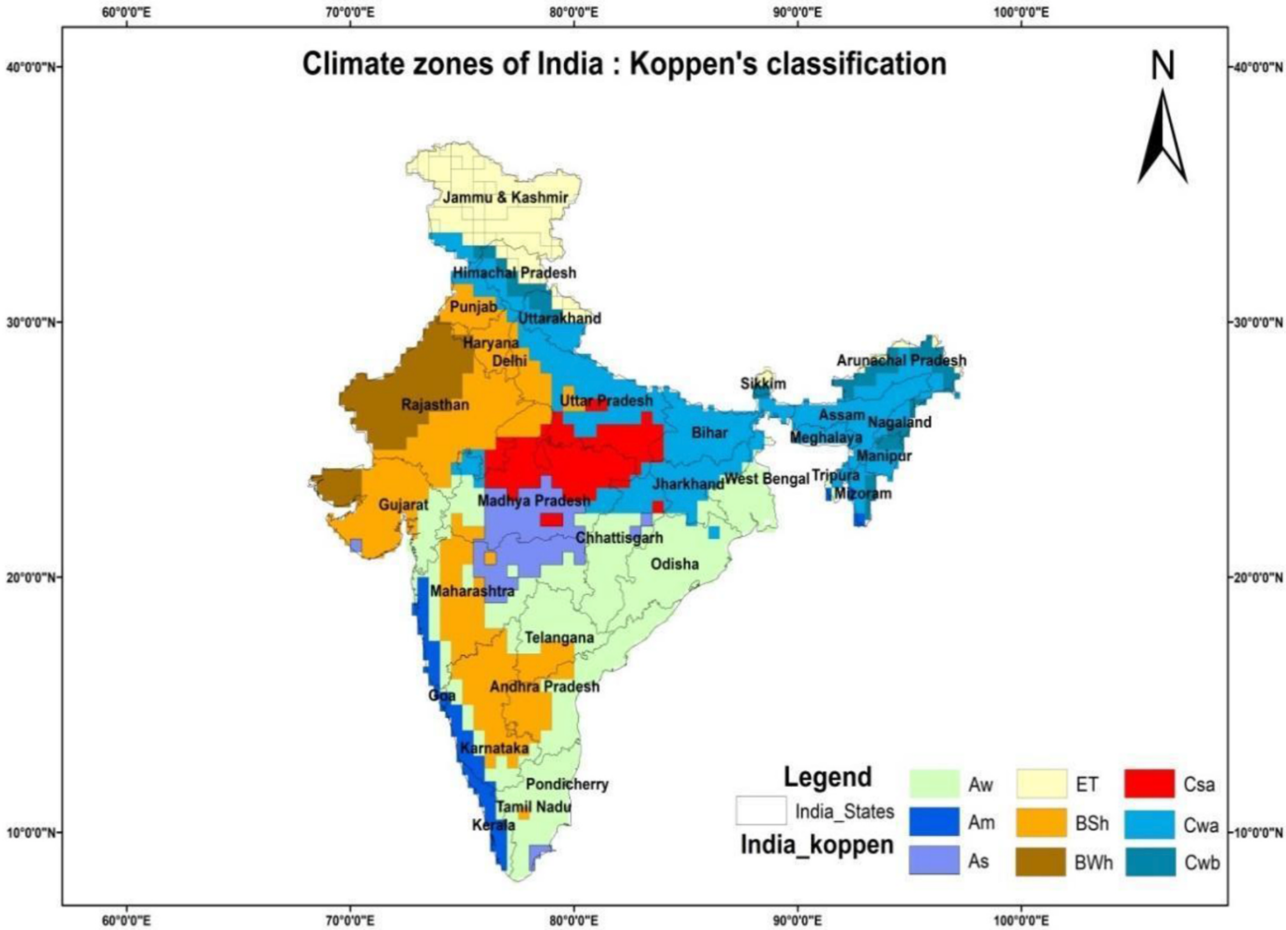


Fig. 1. Map of India showing different climate zones.

Table 1
Regions of India in each climate zones and climate type.

Climate Type	Climate Zones	Regions
Temperate	Cwb	Eastern Part of North East Indian states
	Cwa	North Eastern and Eastern part of India
	Csa	Part of Uttar Pradesh and Madhya Pradesh
Arid	BSh	Semi-Arid regions
	BWh	Arid regions
Tropical	Aw	Southern and Southern Eastern states of India
	Am	Western Ghats
	As	Part of Madhya Pradesh and Maharashtra
Polar	ET	Mountainous region of Jammu Kashmir and Himachal pradesh

impacts of climate change' (UNFCCC, 2015). One of the major consequences of an increasing global temperature is the rise in the occurrences of extreme events. While extreme events were not explicitly discussed in the agreement, they form an important basis for the discussions. The impact of increasing occurrences of such events is especially evident and poses significant threats on livelihoods in most developing member states where disaster management infrastructure is still under-developed while the huge population pressure increases the expected loss estimate (Stephenson et al., 2010). In recognizing the need to avert and minimize the loss and damage resulting from climate change effects (UNFCCC, 2015), it is therefore critical that the relative impacts of a 1.5 °C and 2.0 °C warmer global temperatures on different climate related aspects such as extreme weather events, sea level rise, among others be quantified and compared.

Extreme weather events have large human health and socioeconomic impacts (Robine et al., 2008) based on the event type and are expected to change as a result of climate change. While some extremes such as cold extremes are expected to decrease in frequency under current and future climate relative to pre-industrial conditions (e.g. Christidis and Stott, 2020), a changing climate due to increasing anthropogenic greenhouse gas emissions is expected to increase the probability of most extreme events in terms frequency and severity (Collins et al., 2013; Schar 2016; Krishnan et al., 2020).

The special report of the Intergovernmental Panel on Climate Change (IPCC) concludes that limiting global warming to 1.5 °C will still cause significant negative impacts for the most vulnerable people with the impacts differing across sectors (Allen et al., 2018). In order to assess the potential risks and vulnerabilities associated with incremental increases in global mean surface temperature at regional levels, a proper classification of the impacts under different scenarios as well as the quantification of spatially varying changes in risk is crucially important.

A warming trend has been observed over South Asia in the last few decades, particularly in India, consistent with the global warming signal expected from human-induced climate change (Kumar et al., 2011). Most parts of the densely populated South Asia (SA) region have also witnessed increase in frequencies of extreme high-temperature events (Ding et al., 2010; Zhou and Ren, 2011). When assessing changes in mean surface temperature relative to pre-industrial levels, the multi-model mean of the fifth Coupled Inter-Comparison Project (CMIP5) participating models, based on transient climate states, project that the mean surface temperature over continental Asia increases by 2.3 °C, 3.0 °C, 4.6 °C, and 6.0 °C at warming targets of 1.5 °C, 2 °C, 3 °C, and 4 °C global mean surface temperature, respectively, with stronger

Table 2
ETCDDI extreme rainfall and temperature indices used in the study.

Rainfall Indices			*Temperature Indices*		
PRCPTOT	Annual Total Precipitation in Wet Days	mm/yr	TAS	Mean Annual Surface Temperature	°C
ALTCDD	Maximum Number of Consecutive Days Per Year with Less Than 1mm of Precipitation	days	TX90P	Percentage of Days when Daily Maximum Temperature is Above the 90th Percentile	%
ALTCWD	Maximum Number of Consecutive Days Per Year with At Least 1mm of Precipitation	days	TN90P	Percentage of Days when Daily Minimum Temperature is Above the 90th Percentile	%
RX1DAY	Annual Maximum 1-day Precipitation	mm/dy	TX10P	Percentage of Days when Daily Maximum Temperature is Below the 10th Percentile	%
RX5DAY	Annual Maximum 5-day Precipitation	mm/5dy	TN10P	Percentage of Days when Daily Minimum Temperature is Below the 10th Percentile	%
R99P	Annual Total Precipitation when Daily Precipitation Exceeds the 99th Percentile of Wet Day Precipitation	mm/yr	WSDI	Maximum Number of Consecutive Days Per Year when Daily Maximum Temperature is Above the 90th Percentile	days
R95P	Annual Total Precipitation when Daily Precipitation Exceeds the 95th Percentile of Wet Day Precipitation	mm/yr			
R20MM	Annual Count of Days with At Least 20mm of Precipitation	days			
R10MM	Annual Count of Days with At Least 10mm of Precipitation	days			

Table 3
Median of all model years at different warming levels and duration at each 0.5 °C warming interval.

Warming levels	**Median Year**		**Average Years**
	RCP8.5		
1 to 1.5	2009	2026	17
1.5 to 2	2026	2040	14
2 to 2.5	2040	2052	12
2.5 to 3	2052	2062	11
	RCP 4.5		
1 to 1.5	2009	2029	20
1.5 to 2	2029	2050	21

warming in high latitudes than in low latitudes (Xu et al., 2017). Similar results were obtained in a study specific to the Indian subcontinent (Yaduvanshi et al., 2019). When considering extremes, the multi-model mean of the fifth Coupled Inter-Comparison Project (CMIP5) participating models, project that warm weather related indices, derived from the Expert team on climate change detection and Indices (ETCCDI) are in the general increase under future climate (Sillmann et al., 2013). The extremes were found to increase more under the high emission scenario representative concentration pathway (RCP8.5), for example, the Warm Spell Duration Index (WSDI), that counts the maximum number of consecutive days with a temperature above the 90th percentile of the 1961–1990 base period, will lengthen to 150–200 days under Representative Concentration Pathway RCP8.5, but only to 20–45 days under RCP2.6 by the end of century in the Indian subcontinent (Sillmann et al., 2013). These kinds of analysis are particularly important for a region like India, which the annual report by German watch (Climate Risk Index 2020), which ranks countries according to their vulnerability to extreme weather events indicated that India's overall ranking drastically fell from 14th in 2017 to 5th in 2018. India ranked first in terms of fatalities and second in the world in terms of losses in millions of dollars (Eckstein et al., 2019).

Ratnam et al. (2016) identified north-central and southeastern coastal India as heat wave prone regions. Eleven of India's 15 warmest years have occurred since 2004. Since record-keeping started in 1901, 2018 was the sixth-warmest year for the country. Heat waves over India are significantly correlated with warming of the tropical Indian Ocean and ENSO phenomenon (Rohini et al., 2016).

An increase in heavy monsoon rainfall intensity over South Asia is projected to be about 7% under 1.5 °C and 10% under 2 °C warming compared to pre-industrial conditions (Schleussner et al., 2016; Kumari et al., 2019). Most precipitation extreme events have occurred over the west coast, central and northeast India (Ajayamohan and Rao 2009;

Table 4
Changes in extreme temperature indices (TAS, WSDI, TN90, TX90, TN10 and TX10) presented at various warming levels (WLs) 1.0 °C, 1.5 °C and 2.0 °C under RCP4.5 scenario along with 3.0 °C under RCP8.5 scenario. Changes have been mapped across nine climate zones of India including India as a single spatial unit.

	ZONES	WLs (°C)	TAS (°C)		WSDI (days)		TN90 (%)		TX90 (%)		TN10 (%)		TX10 (%)	
			8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5
IND	IND	1	1.3	1.2	19.1	18.8	12.0	11.5	10.1	9.6	-9.0	-9.2	-6.5	-6.3
		1.5	2.0	2.0	44.3	39.9	20.8	21.7	17.1	18.6	-11.3	-11.3	-8.3	-8.2
		2	2.6	2.6	71.5	66.2	30.9	31.4	26	23.3	-12.3	-12.9	-9.4	-9.8
		3	4.1		131.2		52.2		44.8		-13.4		-10.9	
Temperate	Cwb	1	1.2	1.2	16.9	15.1	13.1	12.4	8.7	9	-8.1	-8.8	-5.5	-5.3
		1.5	1.8	1.8	36.8	31.4	23.7	23.3	16.1	16.1	-10.4	-11.1	-7.4	-7.6
		2	2.5	2.5	60.4	59.8	35.1	34.8	25.1	26	-11.6	-11.9	-8.8	-9.0
		3	3.8		112.0		56.2		43.4		-12.9		-10.6	
	Cwa	1	1.1	1.0	14.5	13.7	11.6	11.4	8.3	8	-9.2	-9.3	-5.1	-5.0
		1.5	1.7	1.6	33.1	32.1	21.3	21.4	14.8	14.6	-11.5	-11.5	-6.7	-6.8
		2	2.3	2.2	58.0	61.1	32.9	32.9	22.5	23.3	-12.8	-12.6	-8.2	-8.5
		3	3.6		114.5		56.4		40.2		-14.1		-10.4	
	Csa	1	1.2	1.1	21.5	21.8	13.5	13.4	11.4	10.5	-11.1	-11.3	-6.7	-6.7
		1.5	1.7	1.7	43.3	41.3	24.4	25.5	18	17.3	-12.8	-13.4	-8.3	-8.6
		2	2.3	2.2	74.0	72.6	35.8	36.2	27	26.9	-13.8	-14.3	-9.6	-10.0
		3	3.5		129.5		58.7		45.7		-14.9		-11.6	
Arid	BSh	1	1.2	1.1	14.8	13.5	10.8	11.1	8.1	7.9	-9.2	-9.2	-5.6	-5.3
		1.5	1.8	1.7	35.0	31.9	19.7	19.3	15.2	13.9	-11.7	-11.7	-7.3	-7.0
		2	2.3	2.2	58.1	54.8	29.7	28.1	21.7	22	-13.2	-13.1	-8.6	-8.5
		3	3.8		115.5		49.5		40.4		-14.1		-10.4	
		1	1.3	1.2	19.9	18.4	12.7	11.9	9.9	10	-9.2	-9.2	-6.1	-5.9

	BWh	1.5	1.9	1.9	38.6	36.9	23.2	22.2	17	17.1	-11.2	-10.8	-7.7	-7.1
		2	2.6	2.6	64.2	63.5	33.8	31.4	24.4	25.6	-11.9	-11.8	-8.8	-8.5
		3	4.0		130.0		54.6		43		-13.3		-10.7	
Tropical	Aw	1	1.1	1.1	23.6	21.3	16.6	15.4	11.9	11.3	-11.8	-12.3	-6.7	-6.9
		1.5	1.7	1.6	46.8	46.1	29.6	28.7	19.5	18.2	-14.3	-14.5	-8.5	-9.1
		2	2.2	2.0	76.7	86.1	41.8	40.2	29.4	30.4	-15.6	-15.6	-9.9	-10.5
		3	3.3		149.0		63.0		49.5		-16.3		-11.9	
	Am	1	1.0	1.0	35.3	36.1	27.9	26.8	16.6	17.2	-15.5	-16.4	-10.2	-11.2
		1.5	1.5	1.5	80.3	79.6	47.0	46.4	31.7	30.5	-17.2	-18.3	-12.2	-13.1
		2	2.0	1.9	131.0	122	62.0	61.0	44.8	41.8	-17.8	-18.9	-13.4	-14.2
		3	2.9		194.0		79.4		61.8		-18.3		-14.7	
	As	1	1.3	1.2	23.6	21.3	12.7	12.2	11.3	10.9	-10.9	-10.5	-6.4	-6.5
		1.5	1.9	1.8	39.1	39.5	22.5	20.9	17	17.1	-13.0	-13.1	-7.9	-8.1
		2	2.4	2.3	62.9	68.5	34.4	30.8	24.8	26.2	-14.4	-14.1	-9.2	-9.7
		3	3.6		127.5		55.2		43.6		-15.6		-11.1	
Colder	ET	1	1.5	1.3	16.1	13.5	10.2	9.4	9.3	8.6	-6.6	-6.4	-6.4	-6.4
		1.5	2.2	2.2	33.9	33.7	17.0	16.8	16.6	16.3	-8.9	-9.1	-8.9	-8.6
		2	3.0	2.9	61.2	53.3	24.1	24.4	25	24.2	-10.0	-10.3	-9.8	-10.3
		3	4.6		128.0		41.5		44		-11.3		-11.5	

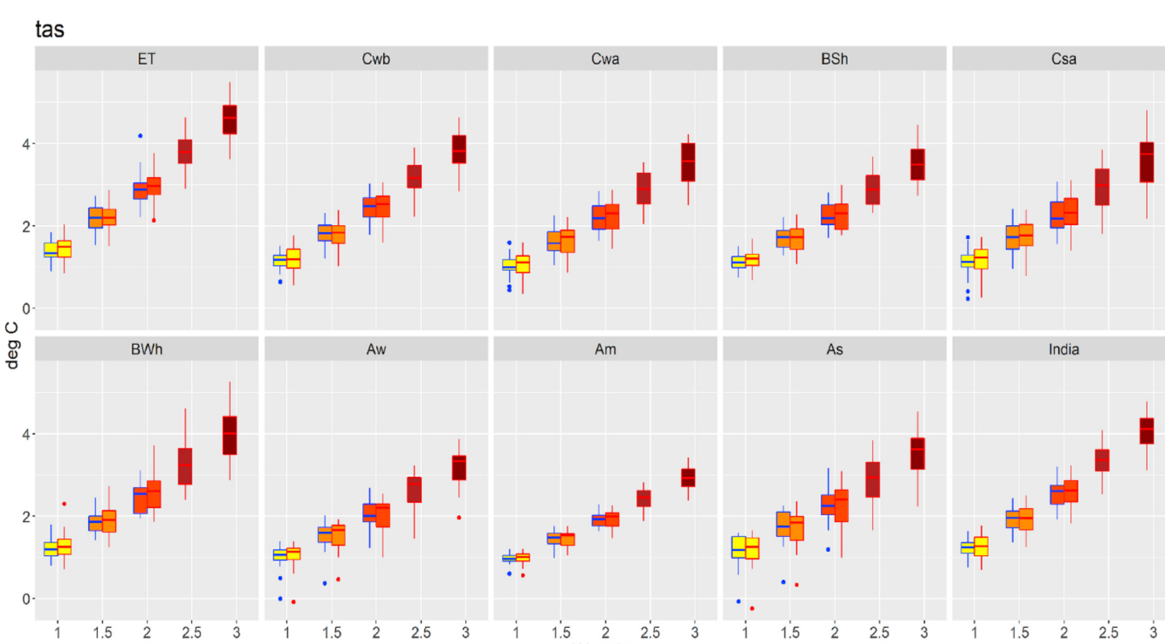


Fig. 2. Box-and-whisker plots for the temperature extreme indices TAS at different warming levels (1, 1.5, 2, 2.5 and 3 °C) under RCP4.5 and RCP 8.5 scenarios. Changes in temperature extremes presented over 9 climate zones including India. The outline colors of box plots indicate two scenarios, blue color represents RCP4.5 and red represents RCP8.5. The model median is indicated by the center line in box plots.

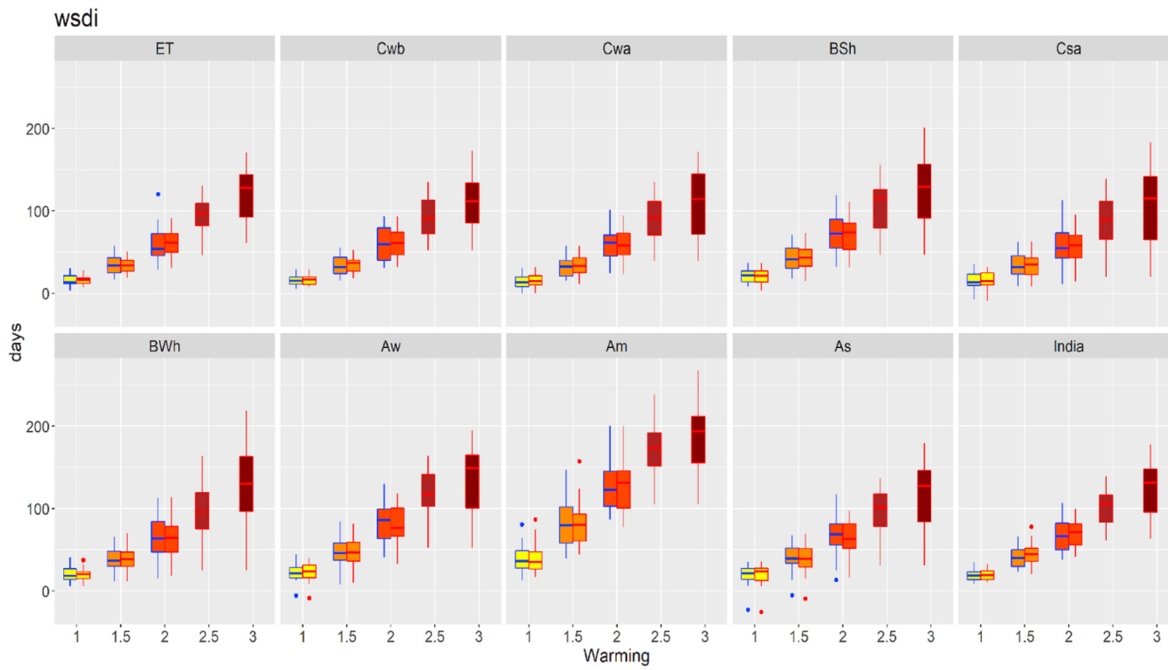


Fig. 3. Box-and-whisker plots for the temperature extreme indices WSDI at different warming levels (1, 1.5, 2, 2.5 and 3 °C) under RCP4.5 and RCP 8.5 scenarios. Changes in temperature extremes presented over 9 climate zones including India. The outline colors of box plots indicate two scenarios, blue color represents RCP4.5 and red represents RCP8.5. The model median is indicated by the center line in box plots.

Goswami et al., 2006). Observations indicate increases in the frequency of the most extreme precipitation events (Gautam 2012; Gautam et al., 2009).

Research quantifying differences in climate extremes between the 1.5 °C and 2.0 °C global Warming Level (WL) is lacking (King et al., 2017). In particular, few studies (Bhowmick et al., 2019; Ali et al., 2018, Singh and Kumar 2019 and Yaduvanshi et al., 2019) have quantitatively examined regional risks for a developing country like India at 1.5 °C global warming. In India, diverse climatic zones coupled with very high dependency (>70% population) on climate sensitive rain fed agrarian economy and at the same time, high exposure to climate-driven hazards has made it one of the most vulnerable country to sustain agrarian economy and rural livelihood (Mandal and Choudhury, 2015; Mandal et al., 2018). Risks that developing countries like India would face if global warming increases to 2 °C as compared to 1.5 °C are higher for heavy precipitation events, including flooding and tropical cyclones of category 4 and 5 over the North Indian Ocean near the Arabian Sea with population residing in Ganga-Brahmaputra delta and Mahanadi delta being more vulnerable (Hoegh-Guldberg et al., 2018).

Given that very little is understood in terms of the difference in risks between the 1.5 °C and warmer global temperatures, it is important to understand how incremental warming above current levels would change the occurrence of extreme rainfall and temperature events in India, especially considering the unfolding change in risk of heavy rain and heat waves in the region under present day conditions. If climate change is already playing a role, then similar events are likely to occur even more frequently as global warming continues in the future (Faust, 2017). Reliable information regarding the relative changes in future risks of extreme events can help local decision makers to adequately address challenges associated with changing patterns of climate extremes as well as develop appropriate adaptation strategies and allocate resources to minimize loss and damage associated with climate change.

In this paper we aim to analyze the possible changes in extreme temperature and precipitation events at annual timescale over different climatic zones of India under stringent stabilization targets (RCP4.5) as well as the unmitigated scenario (RCP8.5) while noting the transient nature of these scenarios do not particularly fit the projected moderate greenhouse gas emission reductions demanded by the Paris Agreement. We use the method of Nkemelang et al. (2018) to identify changes in temperature and rainfall extremes across the various climatic zones of India at different levels of global mean surface temperature (GMST) above pre-industrial levels. We firstly include an assessment of future rainfall and temperature extremes under two scenarios, RCP4.5 and RCP8.5 while Nkemelang et al. (2018) used only RCP8.5. Secondly, we estimate changes in projected extreme indices at 1.0 °C; 1.5 °C and 2.0 °C for RCP4.5 and RCP8.5,extending to 2.5 °C and 3.0 °C for RCP8.5. We then discuss the results, providing a brief assessment of the implications for adaptation and mitigation needs in order to avoid detrimental impacts of climate extremes in India.

2. Study area and data

India is located in the southern part of Asia between latitude 8°4′ N to 37°6′ N and longitude 68°7′ E to 97°25′ E. This region has a tropical climate in the southern part and temperate in the northern region. Based on the Koppen system, India hosts six major climatic subtypes, ranging from arid desert in the west, alpine tundra and glaciers in the north, and humid tropical regions supporting rainforests in the southwest and the island territories (Fig. 1 and Table 1). The Koppen-Geiger climate classification maps were prepared based on datasets from the Climatic Research Unit (CRU) of the University of East Anglia and the Global Precipitation Climatology Centre (GPCC) at the German Weather Service (Rubel and Kottek, 2010). Climate zones are classified based on mean precipitation, temperature and vegetation. Out of five main classes only four cover India, A-Tropical; B-Dry; C-Temperate and E-Polar. The climate in most parts of India is tropical or temperate and hence, the vegetation productivity is controlled by the water/precipitation (Running et al., 2004; Sun et al., 2016).

2.1. Data

Participating model outputs from the fifth coupled inter-comparison project (CMIP-5) are analyzed for temperature and precipitation extremes indices as defined by the “Expert team on climate change

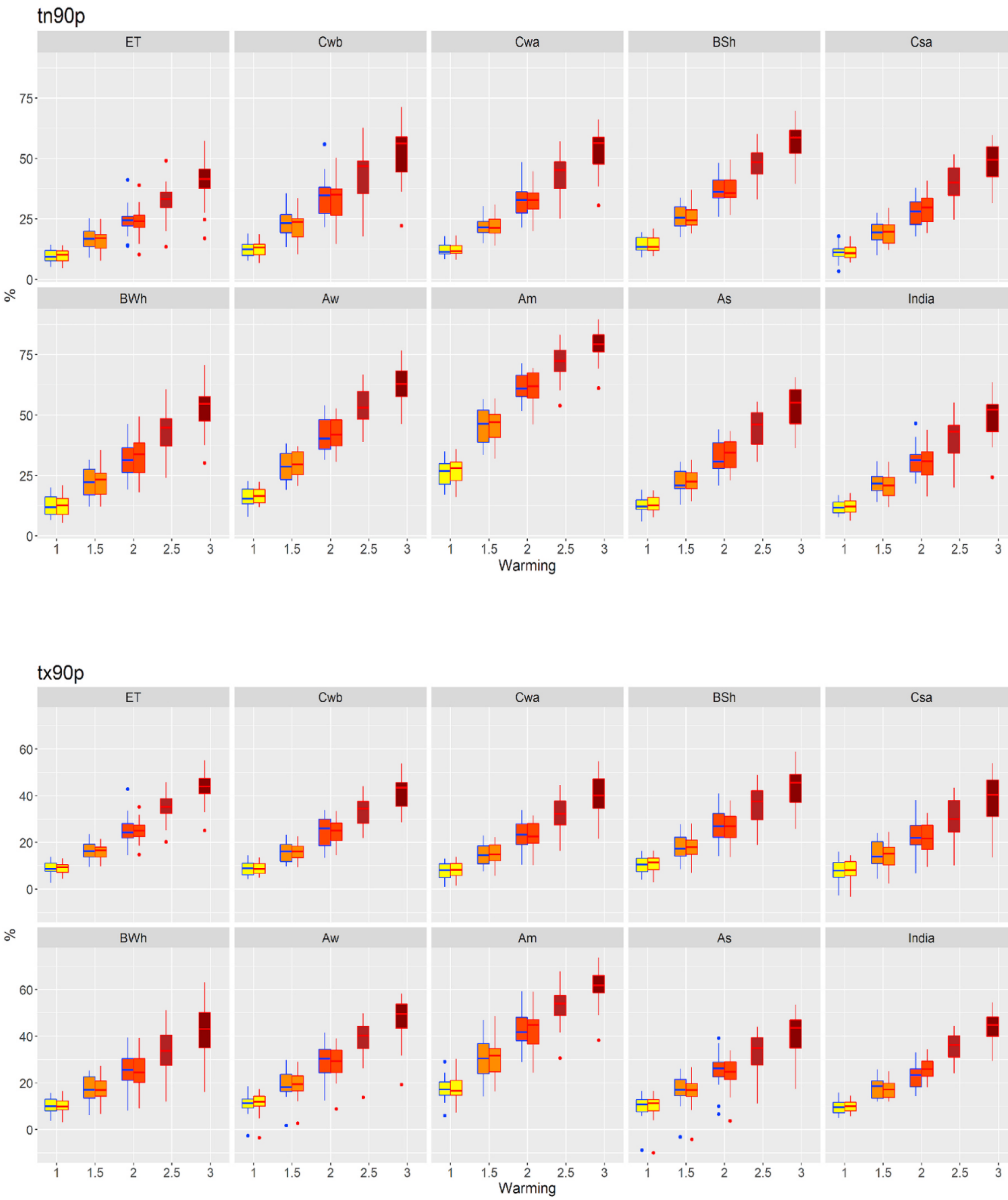


Fig. 4. Box-and-whisker plots for the temperature extreme indices TN90P and TX90 at different warming levels (1, 1.5, 2, 2.5 and 3 °C) under RCP4.5 and RCP 8.5 scenarios. Changes in temperature extremes presented over 9 climate zones including India. The outline colors of box plots indicate two scenarios, blue color represents RCP4.5 and red represents RCP8.5. The model median is indicated by the center line in box plots.

detection and Indices" (ETCCDI). These indices are considered as proxies for extreme temperature and precipitation events. Datasets were downloaded from KNMI climate explorer website of the Royal Netherlands Meteorological Institute in netcdf format. The data is available on a uniform spatial resolution of $1.0° \times 1.0°$ after re-gridding from their original resolution (Sillmann et al., 2013). A total of 24 global climate model outputs are analyzed in the present study under the RCP8.5 while 20 ensemble members are considered under RCP4.5. While it is not ideal to use datasets that are in a transient climate state when addressing a climate that is supposed to have stabilized at a particular warming level (King et al., 2020), we used the current dataset being cognizant of these limitations owing to them being readily available. In the event that any of the participating models has more than one ensemble member, the first member is chosen in order to avoid biasing the results towards certain models. A total of nine indices of precipitation and eight indices of temperature (Table 2) were found to be relevant for Indian climate and have been chosen for analysis.

2.2. Methods

Three warming levels 1.0 °C, 1.5 °C and 2.0 °C above pre-industrial period are defined for both RCPs (4.5 and 8.5) with an extension of

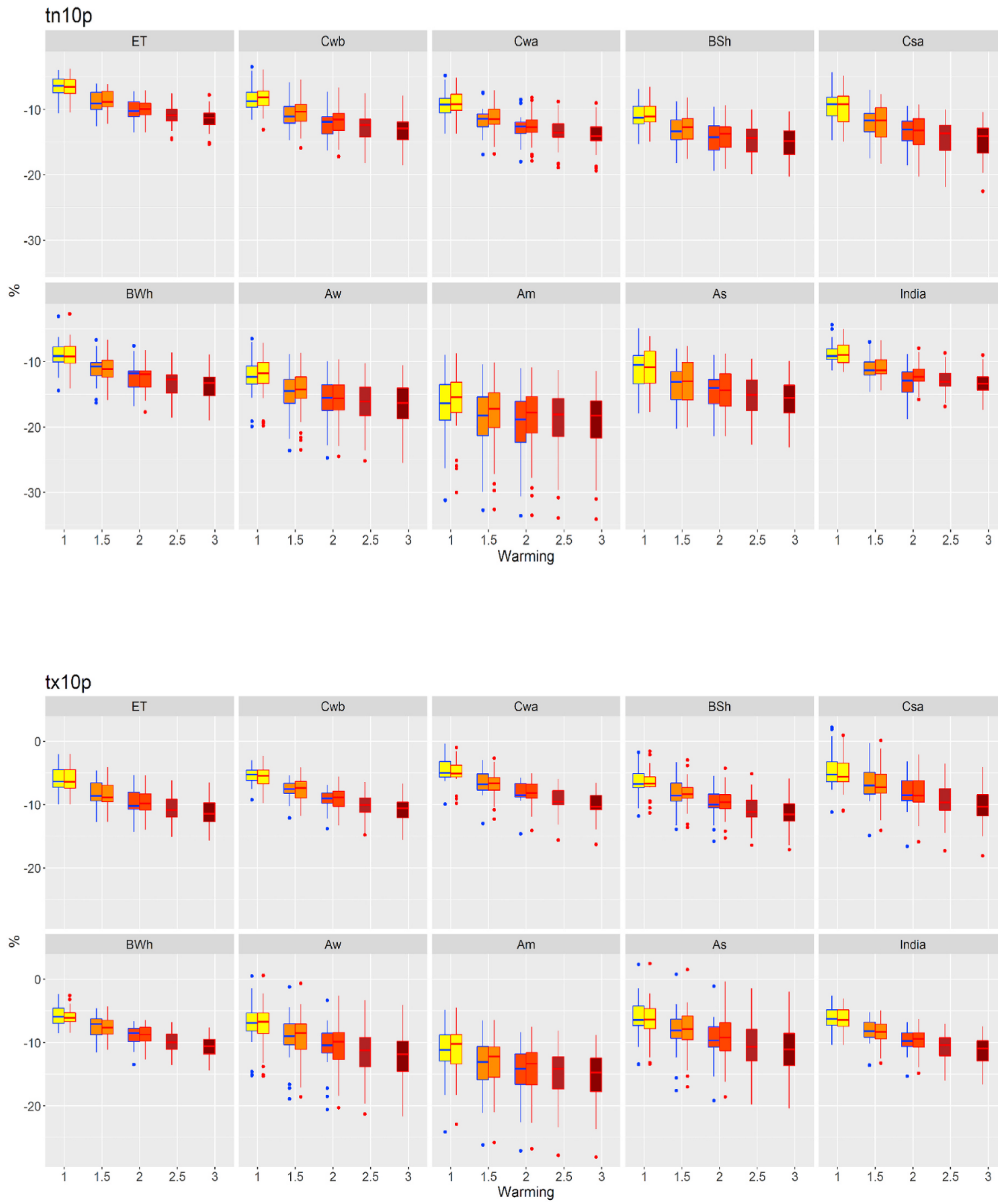


Fig. 5. Box-and-whisker plots for the temperature extreme indices TN10P and TX10P at different warming levels (1, 1.5, 2, 2.5 and 3 °C) under RCP4.5 and RCP 8.5 scenarios. Changes in temperature extremes presented over 9 climate zones including India. The outline colors of box plots indicate two scenarios, blue color represents RCP4.5 and red represents RCP8.5. The model median is indicated by the center line in box plots.

2.5 °C and 3.0 °C for only RCP8.5, defined using time sampling method (Kaplan and New 2006). A reference pre-industrial period of 1861–1900 (40 years) is defined and the changes in the temperature and precipitation extreme indices relative to this period are estimated for the different warming levels (Nkemelang et al., 2018). We note here that for RCP4.5, analysis is limited to 2.0 °C as most of the models do not estimate a global mean surface temperature GMST warming beyond 2.5 °C by the year 2100. For each of the participating ensemble members, the year at which a 31 year running mean of the GMST reaches a particular warming level is used to represent climatology at that temperature threshold. To represent the current climate, we use the 31 year period centered on the year running mean reaches 1.0 °C. We chose to use the 1.0 °C based on estimates of observed GMST increase that slightly exceeded 1.0 °C in the years 2015–2017 relative to 1880–1900 pre-industrial levels (NOAA National Centers for Environmental Information, 2019). Of note is that the 31-year mean GMST for the years ending 2019 only averaged 0.85 °C relative to the 1880–1910 31-year period based on the GISS Surface Temperature Analysis (GISTEMP), version 4 dataset (GISTEMP Team, 2020).

Years at which models reach different warming levels varies as per

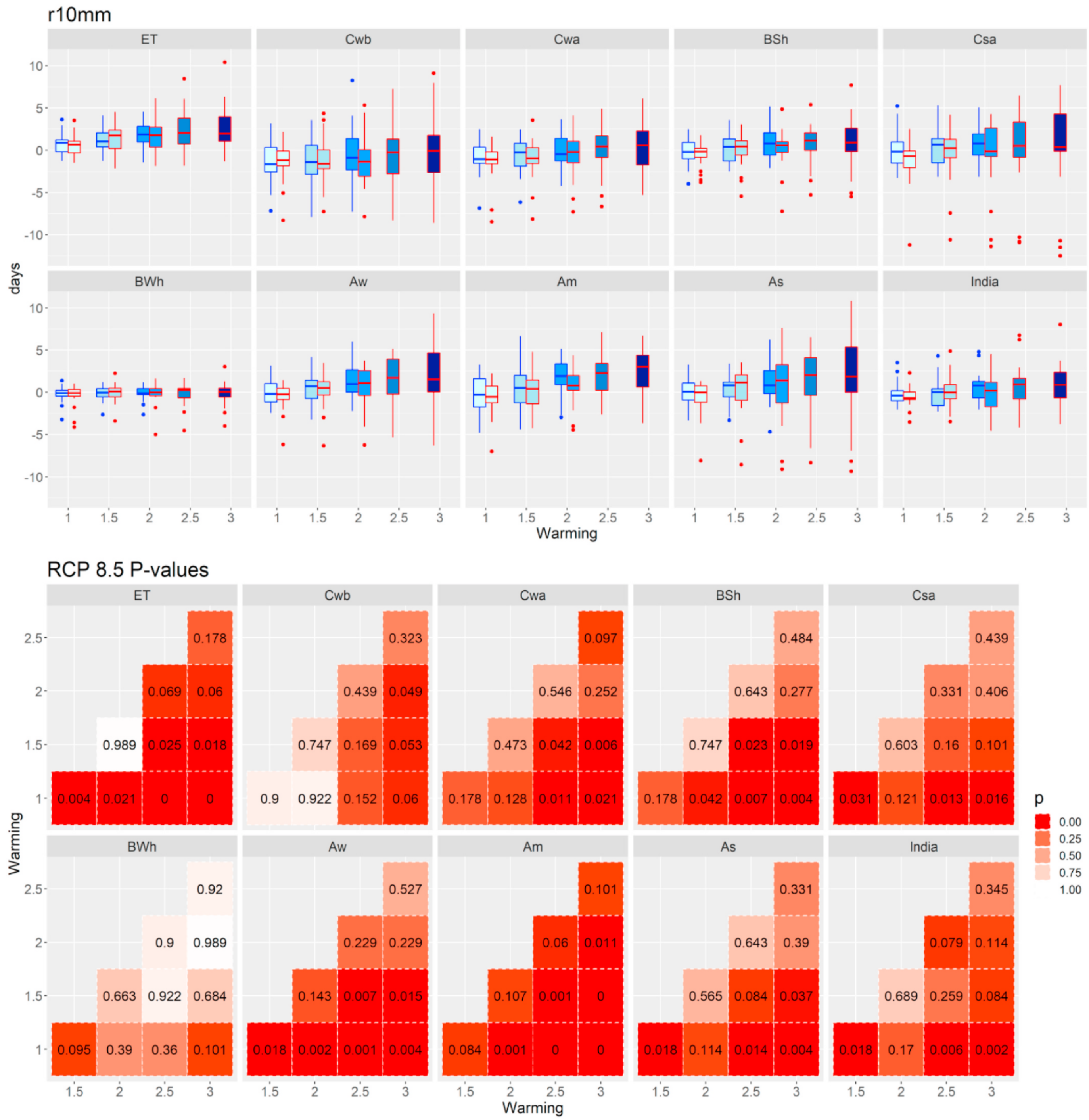


Fig. 6. Box-and-whisker plots for the rainfall extreme indices R10MM, R20MM, RX1, RX5, R95P, R99P, ALTCDD, ALTCWD and PRCPTOT, at different warming levels (1, 1.5, 2, 2.5 and 3) under RCP4.5 and RCP 8.5 scenario. Changes in rainfall extremes presented over 9 climate zones including India. The outline colors of box plots indicate two scenarios, blue color represents RCP4.5, and red represents RCP8.5. The model median is indicated by the center line in box plots. Plot titled RCP8.5 values presenting matrix of p value of Wilcoxon test to show statistically significant values of change for each climate zone at different warming levels.

the physical characteristics of individual models. Median year of the models reaching different warming levels are presented in Table 3. The average number of years it takes for each increment of 0.5 °C keeps decreasing (average across all models) or in other words we are reaching higher warming levels faster. For RCP8.5, it is 14 years to reach 2.0 °C from 1.5 °C, whereas for RCP4.5 it is 21 years.

Nine climate zones as defined using the Koppen-Geiger method are used to subdivide the country (Fig. 1). While previous studies have used administrative boundaries (e.g. Yaduvanshi et al., 2019), we chose to use the climate zones. The decision derives from the fact that weather and climate do not respect political boundaries and the chosen method has been widely used in previous studies to define climate regimes in India (Gunwani and Mohan, 2017). The nine zones cover almost 80% of the geographical area. For each extreme index and participating ensemble member, an area weighted average within each shapefile is calculated on a 31 year climatology centered on the year the model

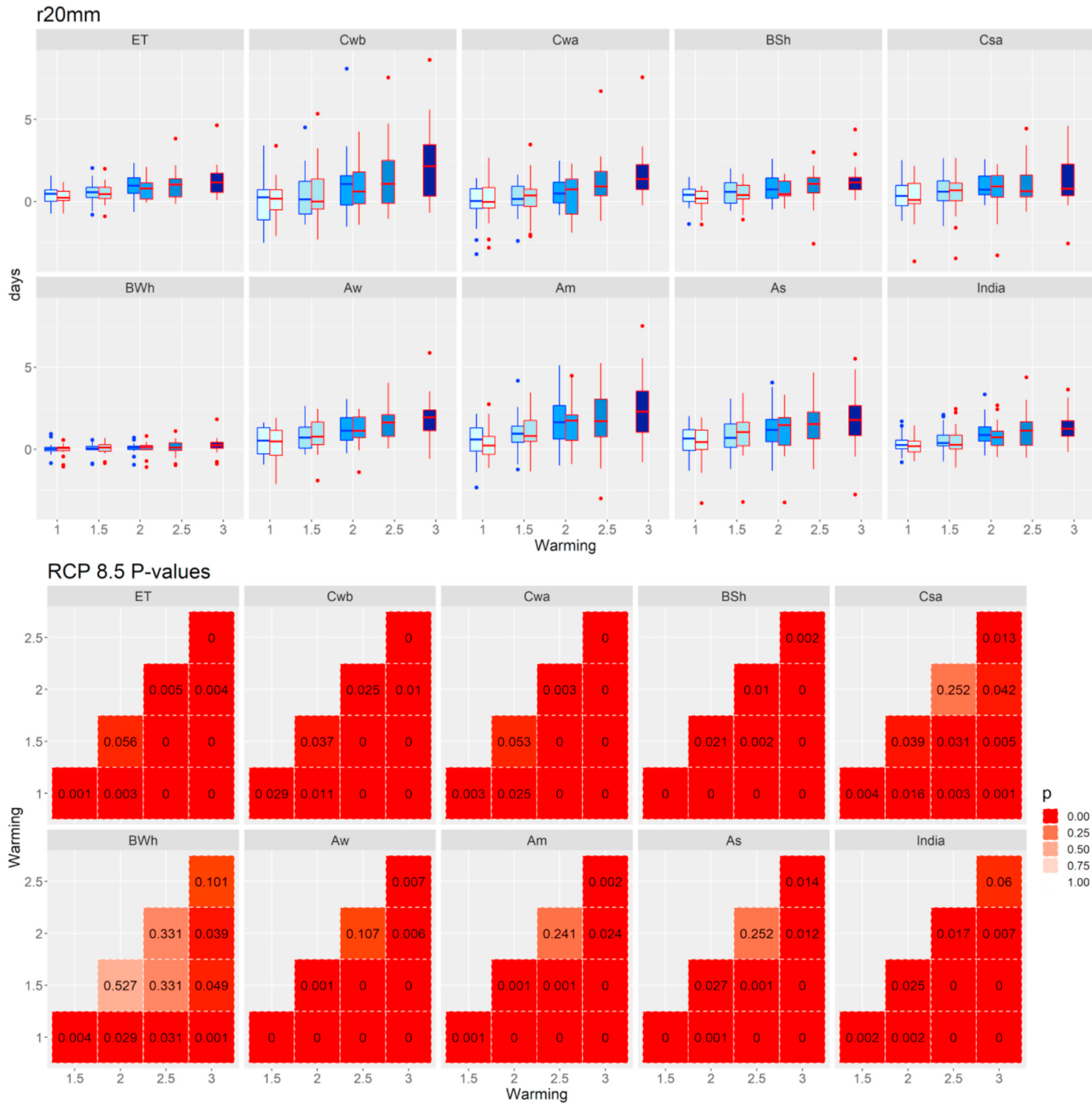


Fig. 6. (*continued*).

reaches a target warming level above pre-industrial. The relative change for each extreme index is then calculated as the difference in climatology at the warming level of interest and the pre-industrial climatology. We use box plots to represent the ensemble spread of change for each rainfall and temperature extreme index calculated for all the 9 climate zones relative to pre-industrial levels. The statistical significance of change based on the distributions of ensembles in their respective warming levels at 95% significance level is evaluated using the non-parametric Wilcoxon paired signed rank test (Silliman et al., 2013b; Nkemelang 2018) and the results presented using heat maps. We only present significance tests for the RCP8.5 while tests for RCP4.5 and the combined ensemble of RCP4.5 and RCP8.5 at 1.0, 1.5 and 2.0 °C are provided as supplementary.

3. Results

3.1. Changes in temperature extreme indices at different warming levels

We present box plots that show the ensemble spread, medians, inter-quartile (IQ) ranges, 1.5*IQ as well as outliers of the changes in the different temperature extreme indices for each region at the respective warming levels (WLs) relative to pre-industrial period under two RCP (4.5 and 8.5) scenarios. Table 4 provides a summary of median changes for the different temperature indices at the respective warming levels relative to pre-industrial levels. Results from the Wilcoxon-paired signed rank test indicate statistically significant changes in all the temperature related extreme indices at all WLs. Maximum temperature related

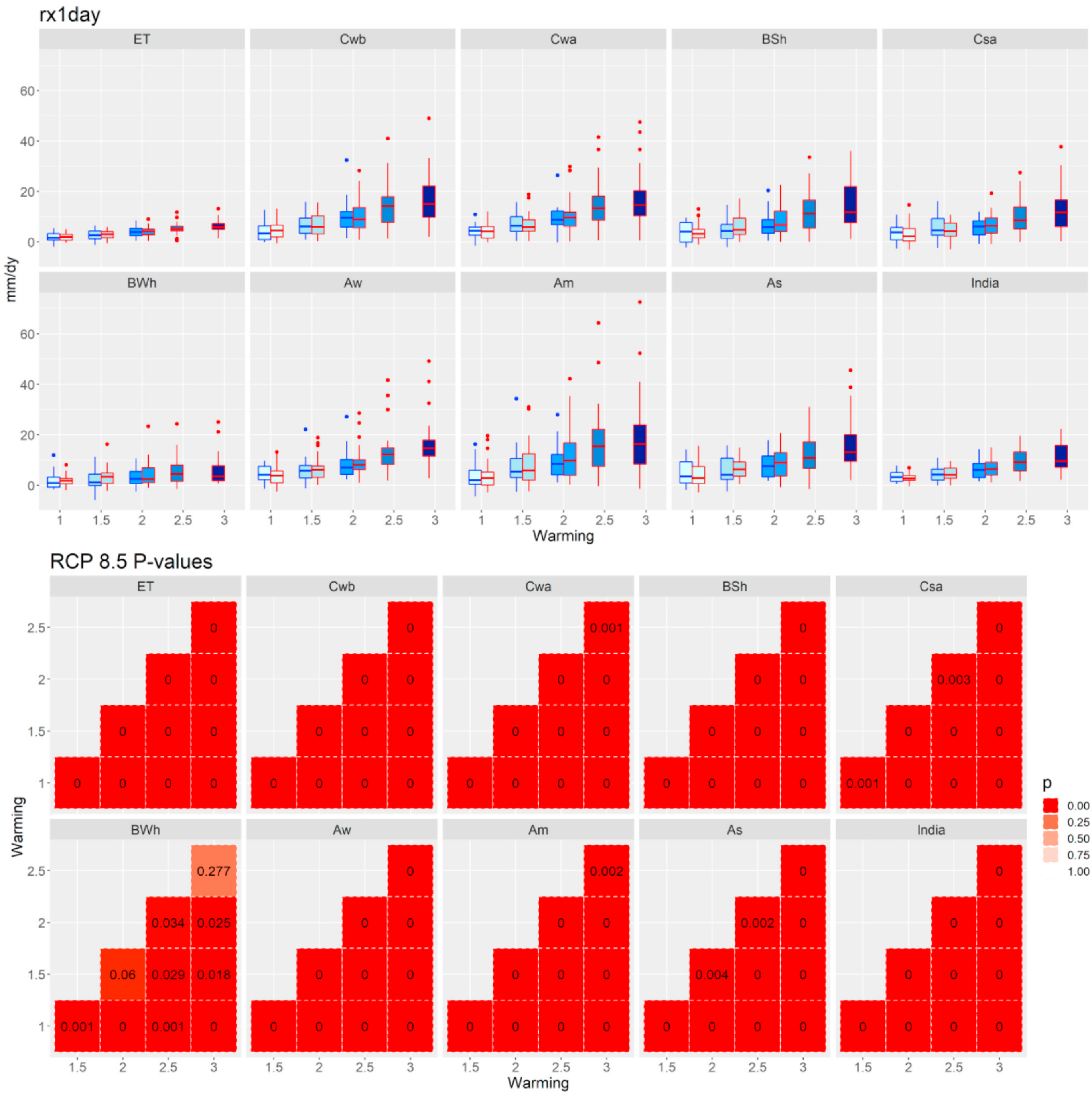


Fig. 6. (*continued*).

extreme indices are projected to increase while decreases in minimum temperature related extreme indices are projected over all climate zones. All models strongly agree that there will be significant increase in temperature and related indices across all the climate zones of India with each GMST 0.5 °C incremental increase under both RCPs (4.5 and 8.5).

Mean annual surface temperature (TAS) change over India is similar for RCP4.5 and RCP8.5 at various WLs with negligible difference. It is noted that at global levels, the main difference in mean temperature change between the two RCPs is prominent as we move towards the end century, this emanates from the fact that greenhouse gas emissions in RCP4.5 peak around year 2040, and then decline while they continuously increase in RCP8.5 (Meinshausen et al., 2011). The mean annual temperature is projected to rise by 4.1 °C (69%) at 3 °C WL and 2.6 °C (52%) at 2 °C WL compared to current climate change (1.3 °C)under RCP8.5 scenario (Fig. 2). The projected increase in mean annual temperature across the climate zones in India is relatively higher than that for global temperature at all warming levels except for the Am climate zone which warms at the level comparable to the global level. Among all climatic zones, the median change in mean annual temperature is highest in colder mountainous areas of Jammu Kashmir (J&K) and Himachal Pradesh (HP) (ET zone) under both RCP4.5 and RCP8.5 (Fig. 2 and Table 4) with differences between the GMST and the zone's temperature increasing by 3 times, being 0.5 °C at 1.0 °C WL (1.49 °C, ranging from 0.8 °C to 2.0 °C) to 1.6 °C at 3 °C WL (4.62 °C, ranging from 3.6 °C to 5.4 °C). Apart from ET zone, part of Western Rajasthan and Gujarat (BWh zone) and Part of Madhya Pradesh and Maharashtra (As zone) are projected to be the second hottest in both RCPs (Fig. 2).

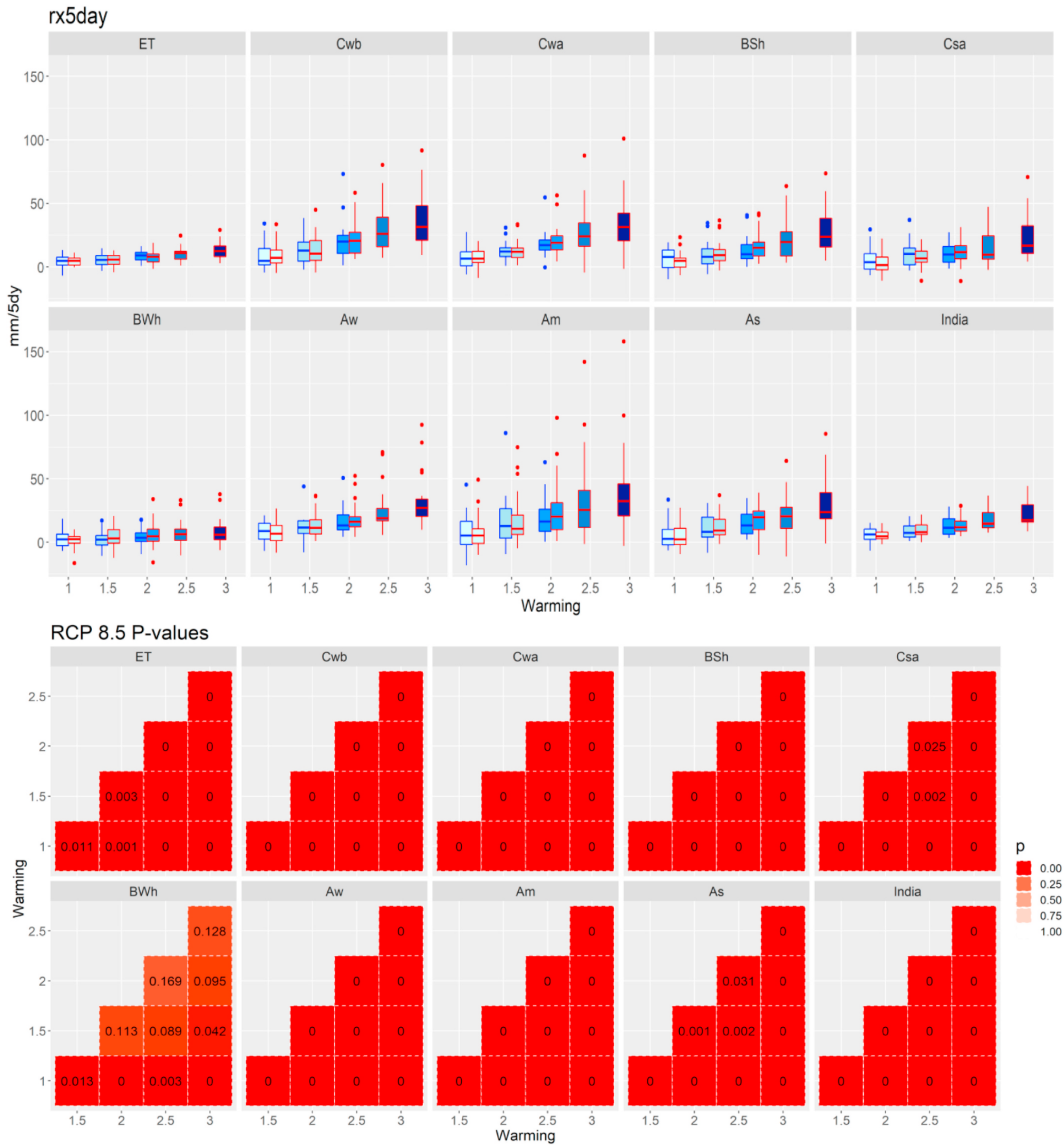


Fig. 6. (*continued*).

Warm Spell Duration Index (WSDI) is expected to rise significantly in Western Ghats (Am zone), Southern and southern eastern states (Aw zone) with increase in median value by 122 days (ranges from 86 to 200 days) at 2 °C global warming under RCP4.5 and 131 days (77–202 days) under RCP8.5 (Fig. 3). Further, among percentile based indices, TN90p (warm nights) and TX90p (Hot days) show the highest change among all indices. However, maximum variation observed for the Am and As zone at 1.5 °C (46%) and 2 °C (61%) temperature rise under RCP4.5 scenario (Fig. 4). Kundu et al., 2017 found a significant increasing trend of temperature rise (1901–2011) along with annual rise of 0.63 °C in maximum temperature in the last 105 years for the state of Madhya Pradesh. In RCP8.5, Am zone is projected to show the highest change at 2 °C (62%) and 3 °C (79%) WLs.

TX10 (Cold days) and TN10 (Cold Nights) are projected to be decrease across all climatic zones of India with highest decrease is observed in Am (−18.85% at 2 °C) under RCP4.5 and (−17.80% at 1.5 °C) under RCP8.5 (Fig. 5). Change in the indices conforms to the findings of many studies which showed significant increase in minimum temperature across Indian regions (Deshpande et al., 2016; Duhan and Pandey 2013; Kothawale et al., 2005). Highest changes in TN10p are

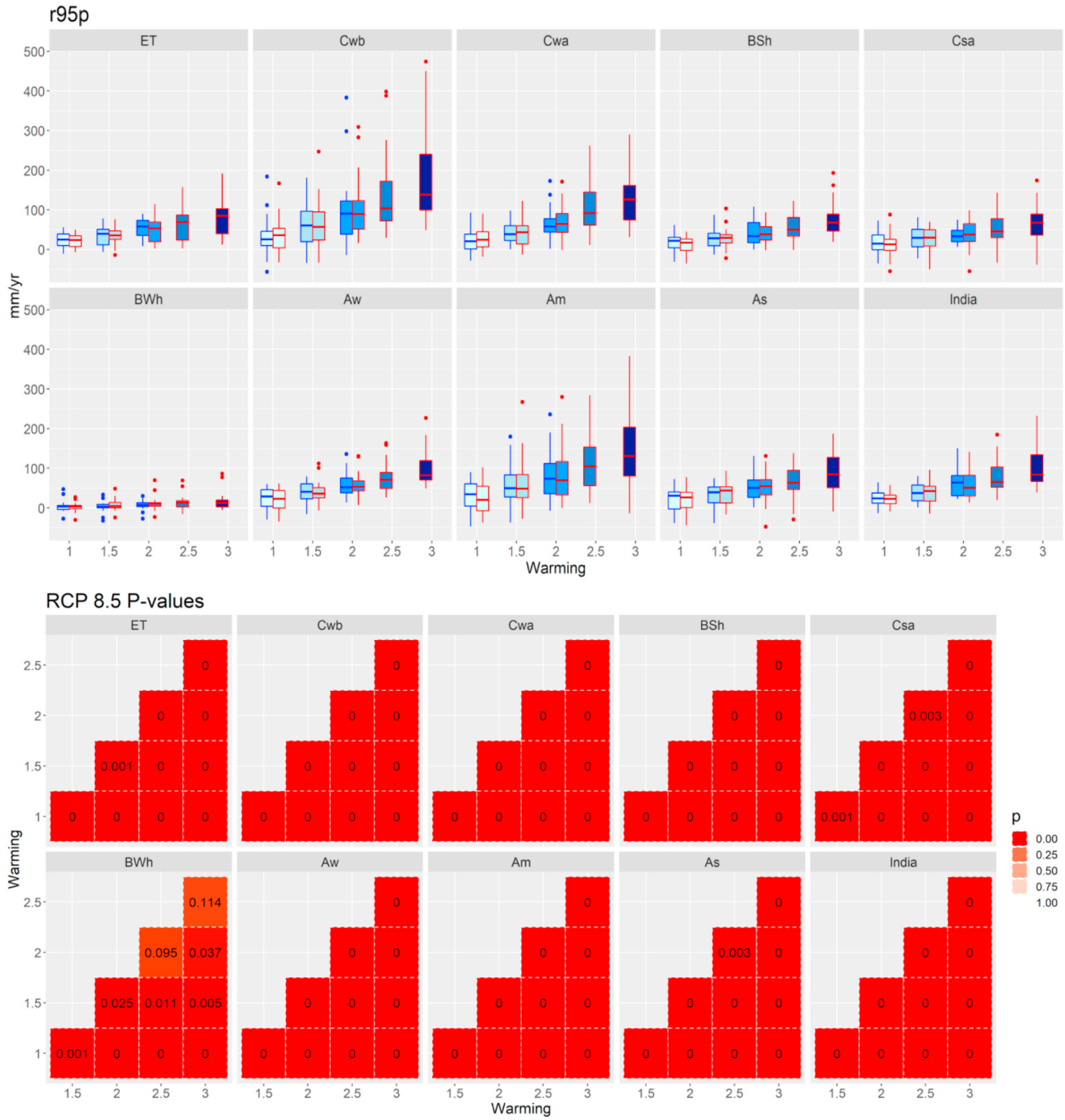


Fig. 6. (*continued*).

projected to decrease over Am, Aw and As zones whereas Am, ET, Bsh and Aw zones are projected to experience the substantial decrease in TX10p (Table 4).

3.2. Changes in rainfall extremes at different warming levels

Changes in rainfall indices do not agree as strongly as temperature on the sign of change across all indices from 1.0 °C to 3.0 °C WL (RCP8.5) and 1.0 °C–2.0 °C WL (RCP4.5). Among nine wet indices, only six indices (PRCPTOT, R20MM, R95P, R99P, RX1day and RX5day) are generally projected to show statistically significant change in the extreme rain events (Fig. 6).

All climatic zones across the country are going to experience an increase in heavy rain events, decrease in consecutive wet spells and increase in consecutive dry spells. It has been reflected in many studies about the increasing extreme rainfall events in the last 100 years over India (Krishnamurthy et al., 2009; Ghosh and Mallick, 2011; Vinnarasi and Dhanya, 2016 and Dash et al., 2011; Yaduvanshi et al., 2017). Study done by Lee and Min, 2018 concluded that extreme precipitation is projected to increase under two warming scenarios and very strongly in 2 °C. Comparison of heavy precipitation indices by end century at 3 °C warming level with current warming level show an increase of 17.6 mm

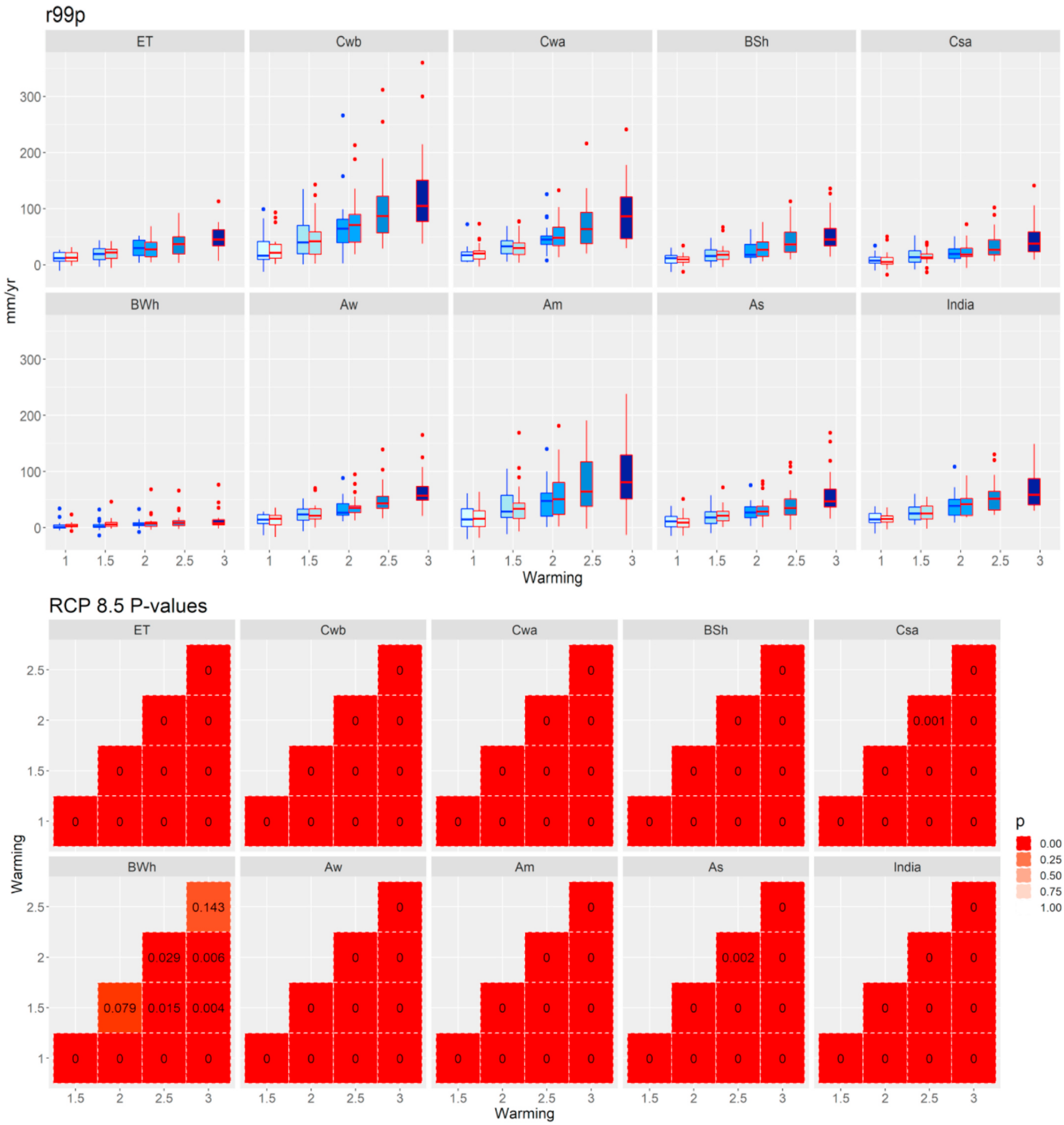


Fig. 6. (*continued*).

for RX5, 58.5 mm for R99p, 45.5 mm for PRCPTOT and decrease by −1.7 days for CWD under RCP8.5 (Tables 5 and 6) for India.

Even though the majority of ensemble members are projecting the reduction in CWD at all five WLs across all climatic zones, projected reduction is found to be statistically significant only in Cwb and Cwa zones. Dash et al., 2007 documented decrease in moderate rainy days in the north east region in the last 54 years (1951–2004).

Capturing regional rainfall through climate models on mountainous terrain comes up with lots of bias and uncertainty. However, models' ability in simulating the past conditions and producing rainfall and temperature for the future century varies significantly. Therefore, findings of precipitation extremes should be interpreted with caution. In case of Am and Cwb zones (High rainfall receiving zones with mountainous terrain) inter-model spread for rainfall extreme indices is very large compared to other zones.

It is observed that for Indian conditions there is strong agreement on the sign of positive change in all heavy rainfall indices (R20mm, R95p, RX5 and RX1days) across the climate zones at all WLs under both RCPs. Even though all the heavy rainfall indices are showing positive change, the highest change in the median value of model ensemble is found over Aw, Am, North Eastern and Eastern part of India (Cwa), Cwb and As zones. In the past, many studies (Roxy et al., 2017) have shown an

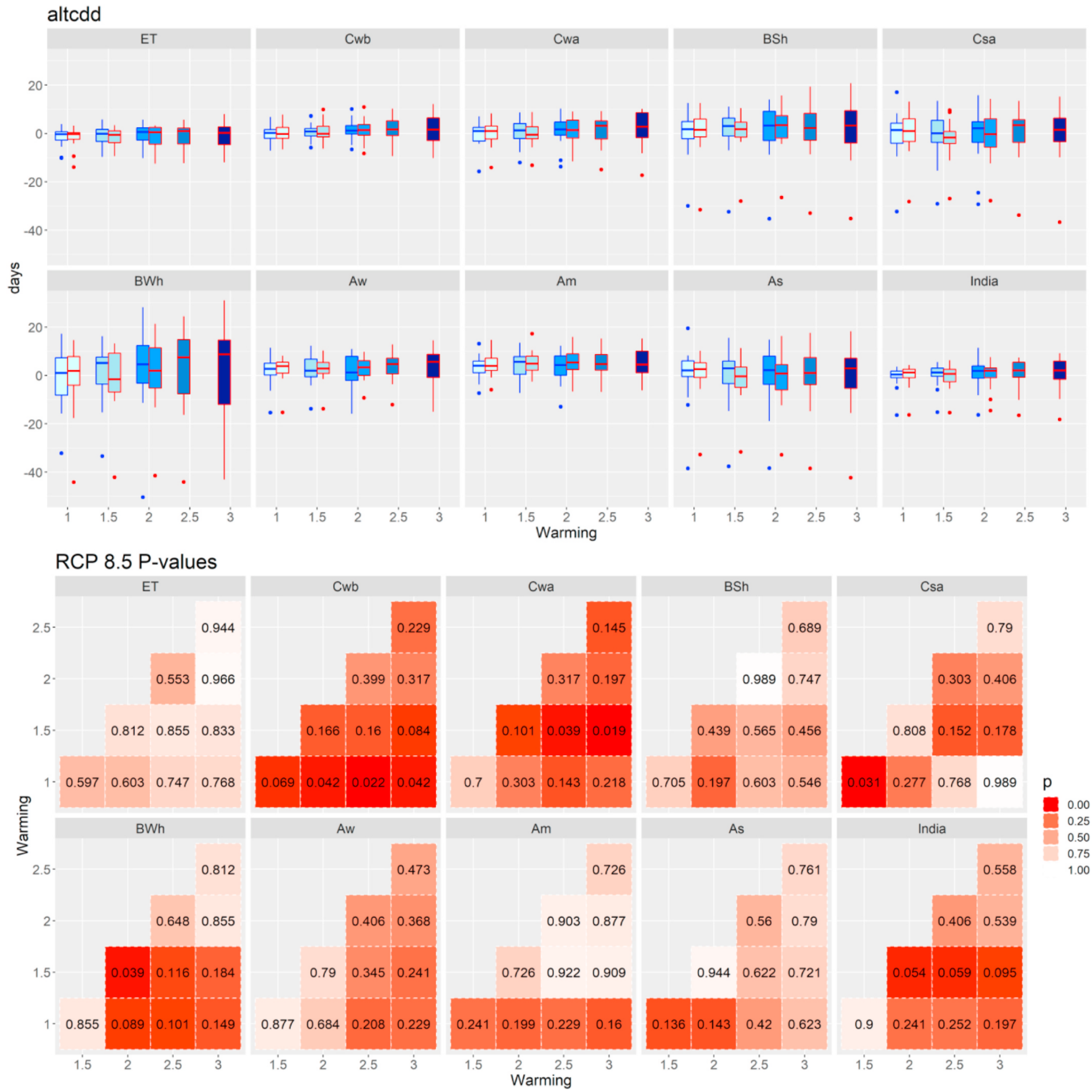


Fig. 6. (*continued*).

increasing trend of extreme rainfall in the above mentioned regions.

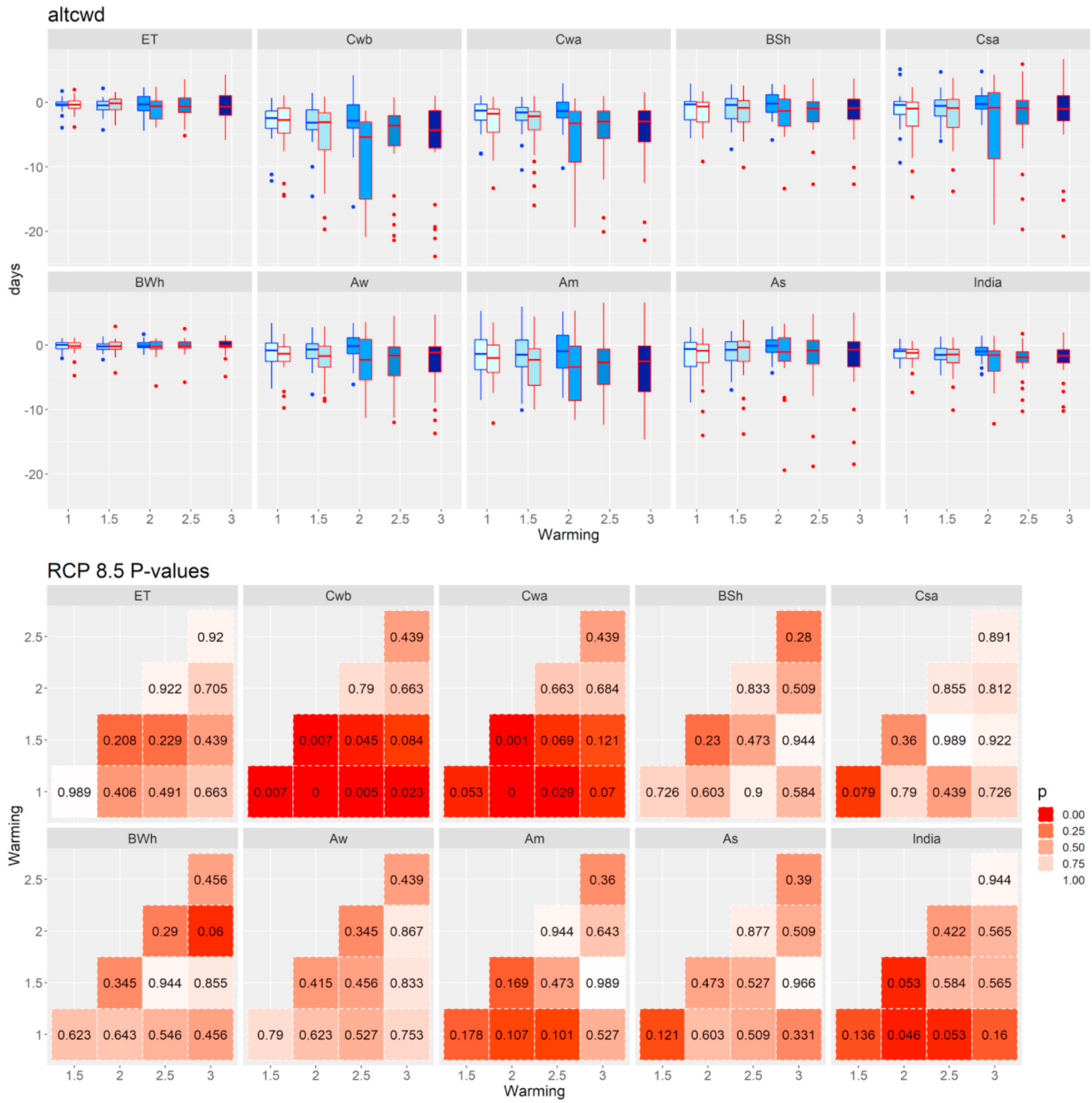
For example under RCP8.5, there is an increase of RX5days in Am (from 5.4 days at 1 °C change to 20.20 days at 2 °C change), As (from 2.2 days at 1 °C change to 19.70 days at 2 °C change). Similarly in other indices such as R95P shows the highest change in Am zone (from 20 mm/yr at 1 °C change to 64 mm/yr at 2 °C) followed by As and Aw. We may note that such types of changes are also observed in other heavy rainfall indices for Aw and As region (Table 5).

ET zone is expected to experience severe changes in extreme temperature and rainfall indices. Mean annual temperature (TAS) showed a highest rise of 75% by the end of the century in RCP8.5 and 53% in RCP4.5. At the same time rainfall extreme has gone up to 66%-RX1, 63%-RX5, 80%-PRCPTOT and 72%-R99P which is not highest compared to other climatic zones, but severe temperature rise would have catastrophic impacts on the rainfall indices of this zone.

4. Discussion and conclusions

More than 80% of individual models are consistent in showing escalated temperature extremes across Indian climatic zones. A very similar distributional pattern is observed for temperature and rainfall extremes in both the RCPs scenario. However, for the 1.5 °C and 2 °C global warming target, the intensity of changes in temperature extremes under RCP8.5 is higher than that under RCP4.5 across India, except for the Tx90 index in the Arid region.

WSDI for India has already increased by 19 days in current warming level (1 °C) and will reach up to 39 days–71 days at 1.5 °C and 2 °C WL under RCP8.5. Out of the seven temperature extreme indices given by



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ETCCDI, WSDI is the only index which counts the duration of warm days exceeding a 90th percentile. WSDI can therefore be considered as a proxy for the duration of heat waves irrespective of the mean temperature of the region. This means two heat wave events with the same duration would be equally severe irrespective of high or low temperature value (Russo et al., 2014). Warm spell of 131 days in a year may not be able to provide in-depth information to take necessary action. Seasonal analysis of temperature extreme indices which are capable enough to capture spatial variability at fine resolution should be considered for further investigation for action oriented research. Real time monitoring and early warning system of heat wave forecast at regional level could help reduce heat stroke deaths in India.

All temperature based extreme indices are showing increase in mean temperature (3.8 °C), WSDI (115 days), TX90 (49.5%) and TN90 (40.4%) and at the same time, significant increases in rainfall extreme such as Rx1 (by 11.8 mm), Rx5 (by 16.6 mm), R95P (by 67.2%), R99P (by 37.8%) and PRCPTOT (by 46.7%) under RCP8.5 scenario at 3 °C warming level, This would bring more heat waves, water loss, and reduction in agricultural production, flash flooding and could affect the ecosystem adversely.

The highest change in mean annual temperature is more pronounced in the ET zone, which almost doubled while moving from 1 °C to 2 °C. Studies with focus on historical trend of minimum temperature showed an increase in Western Ghats and other peninsular part of India (Dash et al., 2007; Mondal et al., 2015). Apart from this, zones such as arid (BWh), semi-arid (BSh) and As showed significant rise in day and night

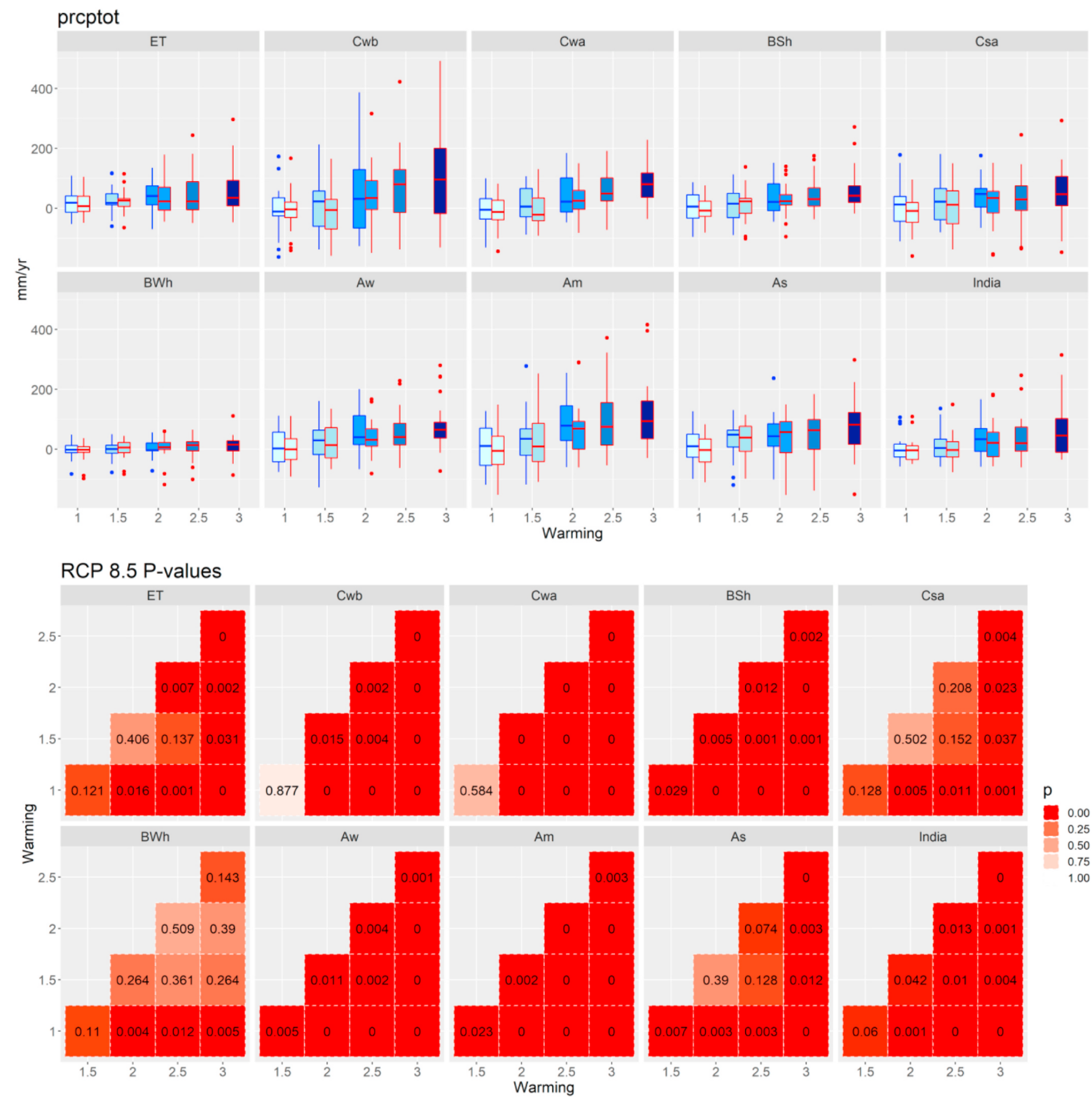

Fig. 6. (*continued*).

temperature. Rising numbers of hot nights could affect human health further in a region where heat stress is already a major problem. According to the Ministry of Earth Sciences (February 2019), states covering zones such as Am, As, BSh and BWh are identified as core heat wave zones of India. Moreover, these zones are projected to show significant rise in all indices of extreme temperature under different WLs.

Many studies are in line with such findings which show 2.5–4.5 °C rise of temperature in the J&K and HP states by the end of century (Joshi et al., 2018). With rise in mean temperature by 4.6 °C, WSDI by 128 days, TX90 by 44% in ET zone, melting of glaciers would be more severe and there would be sharp decline in the area of glaciers which exacerbate rise in sea level. Station located at Sagar Island in Sundarban Delta showed a rate of relative sea level rise close to 8 mm/year (Ghosh et al., 2016). In particular, river basins of the region having high dependency on melt water, this will affect future water availability as well as agricultural productions in the breadbasket of the country (Biemans et al., 2019). These observations are in conformity with larger regional level findings that indicate ice volume in Asia at 1.5 °C scenario will decrease by ≈ 36% and ≈51–64% under RCP4.5 and RCP8.5 respectively (Kraaijenbrink et al. 2017).

Semi-arid regions of the country face changing bio–physical regimes and high vulnerability. Due to limited resources of water, populations mostly rely on rain-fed agriculture.

For India, decrease in CWD index is not a good sign for agriculture production whereas increased WSDI is a measure of drier condition showing substantial increase compared to pre-industrial level.

Table 5
Changes in extreme rainfall indices (R10MM, R20MM, RX1, RX5, R95P and R99P) presented at various warming levels (WLs) 1.0 °C, 1.5 °C and 2.0 °C under RCP4.5 and RCP8.5 with additional 3.0 °C under RCP8.5. Changes have been mapped across nine climate zones of India including India as a single spatial unit.

	ZONES	WLs	R10MM (Days)		R20MM (Days)		RX1 (mm/day)		RX5 (mm/5day)		R95P (mm/year)		R99P (mm/year)	
			8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5
IND	IND	1	-0.7	-0.4	0.2	0.3	2.7	3.3	4.6	6.2	22.6	23.9	15.3	14.4
		1.5	0.0	0.0	0.3	0.4	4.1	4.2	8.1	7.4	42.1	37.1	25.2	25.2
		2	0.2	0.8	0.7	0.9	6.4	6.1	11.8	11.4	50.9	63.3	41.9	38.7
		3	0.9		1.3		9.6		17.6		83.6		58.5	
Tempe rate	Cwb	1	-1.2	-1.6	0.2	0.3	4.5	3.3	7.1	4.6	36.2	25.9	21.7	16.4
		1.5	-1.6	-1.4	0.0	0.1	5.9	6.1	10.5	12.7	56.7	60.5	41.9	39.7
		2	-1.4	-0.9	0.6	1.1	9.0	9.6	20.6	20.0	89.5	90.4	70.9	64.3
		3	-0.1		2.1		15.1		31.5		138.0		104.9	
	Cwa	1	-1.1	-1.1	0.0	0.0	4.1	4.4	6.5	6.5	24.3	21.0	20.2	17.2
		1.5	-1.0	-0.3	0.4	0.2	5.9	6.4	11.9	12.1	43.5	38.5	29.7	32.7
		2	-0.2	-0.5	0.7	0.5	9.7	8.8	18.9	17.1	64.1	58.3	48.1	45.3
		3	0.6		1.4		14.6		31.2		126.0		86.6	
	Csa	1	-0.2	-0.2	0.2	0.4	3.2	4.1	4.7	7.8	17.3	22.1	9.4	11.9
		1.5	0.4	0.4	0.4	0.6	4.8	4.3	9.1	8.0	29.5	28.2	17.9	15.7
		2	0.6	0.8	0.4	0.7	6.8	5.9	15.0	9.9	38.5	33.6	26.6	18.1
		3	0.9		1.2		11.8		23.6		68.0		45.1	
Arid	BSh	1	-0.7	-0.2	0.1	0.3	2.3	3.8	1.4	3.7	12.7	14.8	5.4	7.4
		1.5	0.3	0.7	0.7	0.6	4.3	4.6	6.7	10.2	30.1	29.3	13.3	13.5
		2	-0.1	0.8	0.9	0.7	6.4	6.2	11.7	9.7	37.5	32.8	18.5	19.1

		3	0.4		0.8		11.8		16.6		67.2		37.8	
	BWh	1	-0.1	-0.1	0.1	0.0	1.8	0.9	2.5	2.3	3.6	2.9	2.8	1.1
		1.5	0.1	-0.1	0.1	0.0	3.3	1.2	3.2	2.0	4.6	3.4	5.9	1.8
		2	0.0	-0.1	0.1	0.1	2.5	2.5	4.7	3.4	10.4	6.6	7.2	5.5
		3	0.1		0.2		3.6		6.0		12.1		7.7	
Tropical	Aw	1	-0.3	-0.2	0.5	0.5	3.9	4.2	6.7	8.9	22.6	28.7	15.8	14.3
		1.5	0.5	0.7	0.8	0.7	6.1	5.8	11.5	11.7	35.7	40.3	21.0	23.5
		2	1.1	1.0	1.1	1.1	8.1	7.1	16.0	13.3	53.2	51.8	35.0	26.5
		3	1.5		2.0		14.7		27.2		82.2		56.7	
	Am	1	-0.6	-0.3	0.2	0.6	2.9	2.1	5.4	5.4	20.3	34.4	15.8	14.7
		1.5	0.4	0.5	0.8	0.9	5.9	5.4	10.6	12.8	48.2	49.4	33.6	28.4
		2	0.8	1.9	1.7	1.7	9.8	8.5	20.2	16.4	69.2	73.6	50.4	47.6
		3	3.0		2.3		16.4		32.4		131.0		80.6	
	As	1	-0.1	0.1	0.4	0.7	2.9	3.5	2.3	2.8	26.1	30.5	8.7	11.2
		1.5	1.2	0.8	1.1	0.7	6.3	4.2	9.3	8.2	43.4	39.1	21.3	17.9
		2	1.4	0.8	1.5	1.2	9.0	7.6	19.7	13.3	54.4	50.1	28.6	26.7
		3	1.9		1.8		13.1		23.6		84.6		46.4	
Colder	ET	1	0.7	0.9	0.2	0.5	2.0	1.5	4.6	4.6	23.6	25.0	12.8	12.0
		1.5	1.7	1.0	0.4	0.6	3.1	2.6	5.7	5.5	35.5	40.0	22.0	19.2
		2	1.8	1.9	0.8	1.0	4.1	3.9	7.9	8.9	53.2	58.1	27.7	29.8
		3	2.0		1.2		5.9		12.4		85.0		45.0	

Distribution of rainfall has inclined towards more extreme rainfall events.

In brief, our study highlight notable changes in regional climate extremes when global temperature reaches to 1 °C, 1.5 °C, 2.0 °C, 2.5 °C and 3 °C. Rainfall extremes such as PRCPTOT, R20MM, R95P, R99P, RX1day and RX5day are projected to rise significantly in RCP4.5 and RCP8.5 over Western Ghats, Central India region, North Eastern and South Eastern India.

Indices such as R10mm, R20mm and R95p are showing greater rise in RCP4.5 scenario compared to RCP8.5. This is mainly due to regional 'nonlinear' feedback mechanisms which are involved in precipitation's response to a RCP forcing-includes aerosols, land-use management besides greenhouse gas management. Noticeable change has been seen at 1 °C, 1.5 °C and 2 °C warming level across all the climate zones. When RCP 4.5 is applied more forest cover and less anthropogenic aerosols whereas in RCP8.5 bare lands and more aerosol emission.

Moreover, Large aerosol changes are projected over the Indian region in CMIP5 (Lamarque et al., 2011). Changes in extreme indices would not be solely dependent on anthropogenic greenhouse gas emission, changing aerosol concentration at different time periods may affect the spatio-temporal distribution of indices. Reduction in future aerosol emission in RCP8.5 will lead to a significant increase in rainfall extremes (Zhao et al., 2019).

Additionally, it is crucial to keep in mind the model uncertainty while quantifying the changes, even if our results are statistically significant for most of the rainfall extremes indices. However, in rainfall extreme computation, there is a fair chance of bias despite several models consensus on the same direction of change. In most cases, high rainfall receiving zones in tropics and northern India.

Even though we found the current analysis to be particularly useful and important, we need to note that several limitations of this study exist. Firstly, as noted in the previous sections, we use the CMIP5 datasets that are in a transient climate state, care should be taken not to interpret the results as representative of a stabilized climate state as prescribed in the Paris Agreement. This also means, especially for temperature extremes under the RCP8.5 scenario, the changes sampled at any warming level could be biased towards the last few years of the 31 year sampled period. Important also to note is that, previous studies evaluating the performance of CMIP5 models over the region have been unable to capture key dynamics driving precipitation in the region (Jain et al., 2019; Saha et al., 2014). CMIP-5 models witnessed large biases in magnitude of surface air temperature over North India. (Mishra et al., 2018). Models such as GFDL-ESM2M and MIROC-ESM-CHEM have performed relatively better in capturing temperature extreme events over the Central Indian region. Hot biases became evident due to overestimation of minimum and maximum temperature extremes for most parts of central India (Panjwani and Shweta, 2020).

To add on to this, our current study does not investigate the causes of the changes in the indices, we therefore recommend future studies to investigate further the changes in weather regimes at the respective warming levels.

Action should be taken at regional as well as global level in order to reduce the devastating impacts from climate change. Serious measures need to be taken at the global level to cut down the CO2 emissions by

Table 6
Changes in extreme rainfall indices (ALTCDD, ALTCWD and PRCPTOT) presented at various warming levels (WLs) 1.0 °C, 1.5 °C and 2.0 °C under RCP4.5 and RCP8.5 with additional 3.0 °C under RCP8.5. Changes have been mapped across nine climate zones of India including India as a single spatial unit.

	ZONES	WLs	ALTCDD (Days)		ALTCWD (Days)		PRCPTOT (mm/year)	
			8.5	4.5	8.5	4.5	8.5	4.5
IND	IND	1	1.2	0.3	-1.2	-0.9	-3.3	-4.5
		1.5	0.6	1.3	-1.5	-1.5	-2.5	4.4
		2	2.0	1.9	-1.6	-1.0	21.3	33.6
		3	2.1		-1.7		45.5	
Temperate	Cwb	1	-0.3	0.2	-2.7	-2.5	-3.7	-11.2
		1.5	-0.2	0.8	-3.1	-3.2	-5.7	22.9
		2	1.3	1.2	-5.4	-2.8	33.8	31.4
		3	1.5		-4.3		95.8	
	Cwa	1	1.0	1.0	-1.8	-1.3	-12.7	-4.9
		1.5	-0.5	1.3	-2.2	-1.6	-22.1	5.6
		2	1.4	1.7	-3.3	-1.4	25.2	21.8
		3	2.8		-3.0		80.0	
	Csa	1	1.5	1.8	-0.7	-0.3	-8.2	5.1
		1.5	1.8	3.0	-0.9	-0.4	22.7	15.4
		2	3.4	3.3	-1.3	-0.2	23.8	21.0
		3	3.2		-0.9		41.9	
Arid	BSh	1	1.0	1.4	-1.0	-0.4	-8.7	12.5
		1.5	-1.7	0.0	-0.9	-0.6	11.0	22.1
		2	-0.3	2.1	-0.8	-0.3	34.4	48.0
		3	1.4		-1.0		46.7	
	BWh	1	1.8	1.0	-0.1	0.0	-2.2	-1.7
		1.5	-1.6	5.2	-0.2	-0.2	5.6	0.3
		2	2.0	4.6	-0.2	-0.1	6.2	-3.8
		3	8.8		-0.1		15.0	
Tropical	Aw	1	3.8	2.7	-1.3	-0.8	-0.5	2.7
		1.5	2.8	2.0	-1.7	-0.7	13.8	29.6
		2	3.4	1.2	-2.3	-0.1	31.0	40.1
		3	5.6		-1.2		65.2	
	Am	1	3.9	4.1	-2.0	-1.4	-5.9	10.7
		1.5	4.9	5.6	-2.3	-1.5	9.2	34.8
		2	5.3	4.3	-3.4	-1.0	68.6	78.7
		3	4.5		-2.5		93.5	
	As	1	2.6	2.0	-0.9	-0.6	-3.0	10.4
		1.5	-0.4	2.9	-0.4	-0.7	38.9	48.5
		2	0.7	2.1	-1.1	-0.1	57.2	43.3
		3	2.9		-0.7		82.0	
Colder	ET	1	-0.3	-0.3	-0.4	-0.3	6.8	18.2
		1.5	-0.6	-0.2	-0.2	-0.5	25.5	17.3
		2	0.5	0.7	-0.6	-0.3	22.8	41.2
		3	0.3		-0.7		35.0	

anthropogenic activities. With the help of advanced technology and new innovations, it's vital to understand change in land use/land cover, soil degradation and pollutants at regional level as it affects the internal climate variability at fine scale.

Author contributions

A.Y. performed the simulations, contributed to the analysis of data, and writing of the paper. T.N. helped in numerical experiments, contributed to the writing, and oversaw the work. R.B. helped in interpretation of the results and co-wrote the paper. M.N contributed to the simulations and formulation of the research goals.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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